Single-parameter quantized charge pumping in high magnetic fields

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We study single-parameter quantized charge pumping via a semiconductor quantum dot in high magnetic fields. The quantum dot is defined between two top gates in an AlGaAs/GaAs heterostructure. Application of an oscillating voltage to one of the gates leads to pumped current plateaus in the gate characteristic, corresponding to controlled transfer of integer multiples of electrons per cycle. In a perpendicular-to-plane magnetic field the plateaus become more pronounced indicating an improved current quantization. Current quantization is sustained up to magnetic fields where full spin polarization of the device can be expected.

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Generating well defined currents by manipulating single charges has attracted considerable interest in the last two decades from both fundamental and applied points of view [1]. A particular potential of application lies in the field of metrology to provide a link between time and current units [2]. Different approaches have been studied, such as arrays of tunnel-connected metallic islands controlled by a number of phase shifted ac signals [3, 4, 5, 6] or semiconducting channels along which the potential can be modulated continuously [7, 8, 9, 10, 11]. The pumping mechanism demonstrated in Ref. [10] allows gigahertz pumping comparable to surface-acoustic-wave pumps [8] while promising a higher degree of control. It employs three electrodes of which two are modulated at a fixed phase shift and with different amplitudes. In Ref. [11] it was shown that a single modulated voltage signal is sufficient to operate the pump and a numerical investigation indicated the importance of the tunnel barrier shape for improving the accuracy. A possible way to manipulate these tunnel couplings might be the application of a magnetic field owing to its influence on the wave function and the corresponding rearrangement of electrons between quantum states (see for instance [12]). Therefore the operation of such a single-parameter charge pump has been realized in the presented work when a perpendicular-to-plane magnetic field was applied.

Two devices have been investigated which were both realized in an AlGaAs/GaAs heterostructure with a carrier concentration of $2.1 \times 10^{15} \, \mathrm{m}^{-2}$ and a mobility of $97 \, \mathrm{m^2/Vs}$ in the dark. A 700 nm wide wire connected to two-dimensional electron gases was created by wet-etching the doped AlGaAs layer. This channel is crossed by two 100 nm wide Ti-Au finger gates of 250 nm separation. A schematic is shown in the inset of Fig. 1(a). A quantum dot (QD) with discrete quasibound states between the gates can be created by applying sufficiently large negative voltages V_1 and V_2 to gate 1 and gate 2,
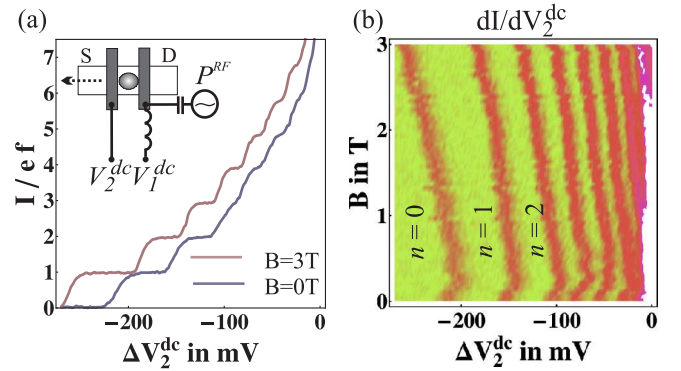
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FIG. 1: (Color online) (a) Pumped current I normalized by ef versus the variation of the dc voltage applied to gate 2, ΔV_2^{dc}. The inset shows a schematic of the device, with the dashed arrow indicating the direction of the pumped electrons. S and D indicate source and drain contacts. (b) dI/dV_2^{dc} in arbitrary units as a function of applied B-field and ΔV_2^{dc}. The number of electrons, n, pumped per cycle is specified in the figure. The measurements where performed in device 1 at $f = 50 \, \mathrm{MHz}$, base temperature $T = 40 \, \mathrm{mK}$ and power $P^{RF} = -16 \, \mathrm{dBm}$.

respectively. An additional radiofrequency (rf) signal is coupled to gate 1. The resulting voltages are therefore $V_1 = V_1^{dc} + V_1^{ac} \cos(2\pi f t)$ and $V_2 = V_2^{dc}$ at gate 1 and gate 2, respectively. If the oscillation amplitude is high enough, then the bound state drops below the Fermi level during the first half-cycle of the periodic signal and can be loaded with electrons from source. During the second half-cycle the bound state is raised sufficiently fast to avoid backtunneling and electrons can be unloaded to the drain. The resulting current changes in steps of ef as the voltage parameters are varied, where e is the electron charge and f is the pumping frequency. For a detailed discussion we refer to Ref. [11].

The measured characteristic for device 1 is shown in Fig. 1. The measurements were performed at a base temperature of $T = 40 \, \mathrm{mK}$. The pumping frequency was chosen to be $f = 50 \, \mathrm{MHz}$ at a rf power of $P^{RF} = -16 \, \mathrm{dBm}$.

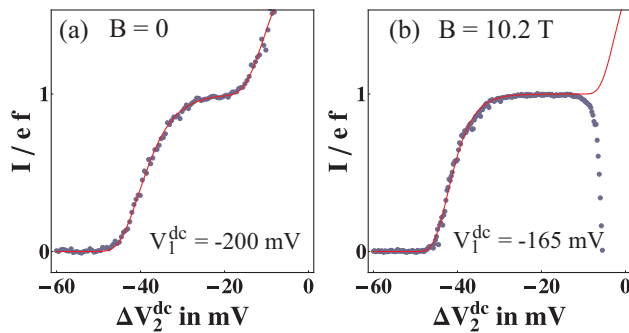FIG. 3: (Color online) Pumped current I normalized by ef at $f = 500$ MHz through device 2 versus the variation of the dc voltage applied to gate 2, ΔV_2^{dc}, at fixed V_1^{dc}. In (a) no field was applied, while (b) shows the characteristic for $B = 10.2$ T. The gate characteristic was fitted using Eq. 3 together with the following parameters: For zero field (a), $V_a = -40.4$ mV, $V_b = 4.6$ mV, $\Delta_2 = 6.4$ while for the measurements at $B = 10.2$ (b) the values $V_a = -42.32$ mV, $V_b = 3.31$ mV, and $\Delta_2 = 12$ were used.

The data in Fig. 3 are modeled by including the first two plateaus, i.e. $n = 2$. Parameters V_a and V_b are chosen so that always $\Delta_1 = 0$. In this way, Δ_2 determines the flatness of the first plateau independently of position and scale of the plateau structure along the voltage axis. The parameters for modeling the data are given in Fig. 3. In particular, $\Delta_2(B = 0) = 6.4$ for pumping in zero field, while $\Delta_2(B = 10.2\,T) = 12$ and is significantly increased when the field was applied. $\Delta_2(B = 10.2\,T)$ was chosen under the assumption that the second plateau would start just outside the region where pumping can be achieved. Operating the pump exactly in the middle of the ef plateau this model predicts a deviation from the exact value of $1 - \exp(-\exp(-\Delta_2/2))$, so that B-field operation has reduced the error by an order of magnitude from 4 % to 0.3 %. The physical meaning of Δ_2 may be related to how the functional dependence of $\Gamma_0(V_1)$ varies between the different charging states.

Note that for the investigated devices full spin polarization of source and drain (filling factor one) occurs at an applied field of 8.9 T. Therefore at the higher applied field of 10.2 T only spin polarized electrons are loaded from the source. As the spin flip times of the electron on the quantum dot should be significantly longer than the average hold time during pumping [14] fully spin polarized quantized charge pumping through the device can be expected. Furthermore the spin state of source and drain at the given field could be independently tuned via the carrier density by additional top gates on each side of the QD. Such a device might thus serve as a clocked source of spin polarized single electrons for spin electronics and quantum information processing.

From the investigation above we conclude that the accuracy in single-parameter pumping can be improved by the application of a high perpendicular-to-plane magnetic field [15]. The phenomenon of quantized pumping can be sustained in high fields in contrast to the conceptually related charge pumps using surface acoustic waves [16], allowing spin polarized quantized charge pumping. So far we have tested and observed quantized pumping in such devices up to fields of 16 T. The magnetic field as an additional control parameter makes single-parameter pumps in AlGaAs/GaAs heterostructures promising candidates for an accurately quantized, large-current source as needed for fundamental experiments in metrology and quantum electronics.

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